Photosynthetic Carbon Assimilation in a Shootless Orchid, *Chiloschista usneoides* (DON) LDL

A VARIANT ON CRASSULACEAN ACID METABOLISM

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ABSTRACT

Photosynthetic carbon assimilation in the roots of a shootless orchid *Chiloschista usneoides* (DON) LDL involves the synthesis and accumulation of malic acid from CO₂ in darkness. Malic acid is consumed in the light.

The roots do not possess stomata or any means of diurnally regulating the diffusive conductance of the pathway between the internal gas phase of the plant and the atmosphere. Regulation of internal CO₂ concentration near to atmospheric levels avoids a large net loss of CO₂ to the atmosphere during malic acid consumption in the light.

The water-absorbing function of the velamen conflicts with the photosynthetic function of the roots. Plants with water-saturated velamina do not acquire CO₂ from the atmosphere at night.

Photosynthesis in many epiphytic orchids involves the nocturnal acquisition of CO₂ and accumulation of malic acid followed the next day by the release of CO₂ from malic acid and its utilization in the reductive pentose phosphate pathway. Stomatal resistance is high at night and low during the day. Clearly these plants exhibit CAM (1).

Another commonly observed feature of such orchids is the possession of Chl-containing aerial roots and it has recently been shown that these roots, like leaves, exhibit the diurnal fluctuation in acid content and CO₂ exchange pattern characteristic of CAM (6). The aim of the present work is to extend information on the photosynthetic metabolism of orchid roots.

The experimental material used in this study is *Chiloschista usneoides*, a member of the group known as shootless orchids which has been eloquently described by Benzing et al. (2). In the mature vegetative state, *C. usneoides* consists of Chl containing velamentous roots which encircle and adhere to the substrate tree branch. The shoot is represented only by a very short structure from which the roots are produced. Leaves are usually absent although small leaves may occasionally be present, particularly during the early stages of development of the plant. Virtually all photosynthetic carbon assimilation takes place in the roots of *C. usneoides* and the use of this plant avoids problems associated with the possibility of translocation of photosynthetic products between leaves and roots encountered in plants which possess both of these organs.

MATERIALS AND METHODS

Plant Material. The shootless orchid *Chiloschista usneoides* (DON) LDL was grown outdoors or in a controlled environment cabinet with: 12 h photoperiod (200 µmol m⁻² s⁻¹ PAR); day temperature 26 to 30°C; night temperature 25°C; RH > 70% day and night.

Plants were thoroughly soaked by spraying with water once each morning. When fully engorged, the velamen, which appears silvery when dry, becomes transparent and the roots appear dark green in color. In some plants, the velamen was heavily colonized by green algae. Such plants were not used for experimental work.

Photoperiod. In all experiments, unless specifically noted, experimental photoperiods coincided as much as possible with the natural photoperiod (7–19 h).

Measurement of Acid Content. Duplicate samples of roots weighing approximately 1 g were boiled in distilled H₂O for 15 min and the extracts were then titrated to the phenolphthalein end-point with 0.01 N NaOH and the average acid content calculated. Because the extracts contained varying proportions of a mixture of acids, the data are expressed as µeq of acid.

CO₂ Exchange. The CO₂ concentration in air which had passed at a rate of 300 ml⁻¹ min⁻¹ through a glass cuvette maintained at 25°C containing a whole plant was estimated by open-system, differential analysis using a Beckman model 865 IR gas analyzer. Water vapor was removed from the usually saturated gas stream by absorption in silica gel prior to analysis. Calibration of the system utilized standard CO₂ mixtures. Plants were illuminated by a 700 w Philips mercury lamp and PAR was measured using a LI-COR quantum meter with a LI-190 SB sensor. Experiments were repeated at least four times.

Products of Dark ¹⁴CO₂ Fixation. Radioactive CO₂ (50 µCi in 1 µmol) generated from NaHCO₃ by the addition of lactic acid was injected through a serum bottle stopper into darkened 50-ml flasks containing intact plants. After incubation at 25°C for 14 h, the plants were killed and extracted in boiling ethyl alcohol.

The ethanol extract was analyzed by paper chromatography and autoradiography using propan-1-ol, ammonia, water, and phenol; water as solvents. The identity of radioactive compounds from two experiments was confirmed by co-chromatography and relative amounts of radioactivity measured by Geiger Müller counting of the chromatograms.

Internal CO₂ Concentration. Using a microsyringe, 10-µl samples of gas were removed from the internal atmosphere of plants under the conditions detailed in the results section and analyzed by GC on Porapak Q at 100°C. Carrier gas was N₂ at 15 ml/ min. Following separation, CO₂ was hydrogenated to produce CH₄ (Pye Unicam catalytic converter) and then detected and quantified using a flame ionization detector. Standard gas mixtures were used to calibrate the method. Since there are open pathways between the internal gas phase of the root and the atmosphere, the withdrawal of samples from the internal atmosphere by syringe will inevitably result in 'contamination' of the
differences sample using accumulated during the following morning—a fluctuation of more than 70 μeq g⁻¹ fresh weight (Fig. 1). Subsequent measurements made at more widely spaced intervals (also shown in Fig. 1) confirmed the substantial changes in titratable acidity. These experiments used plants growing in the natural environment and while the first 2 d were bright and cloudless (900 μmol m⁻² s⁻¹ PAR at the plant surface at noon) the final day was cloudy (variable PAR with approximately 400 μmol m⁻² s⁻¹ at the plant surface at noon). The level of acid at the end of the cloudy day was 65 μeq g⁻¹ fresh weight compared with less than 40 at the end of the bright days.

Acid fluctuations were also studied in plants which had water-saturated velamina throughout a 24-h cycle. Because the velamen absorbs a great deal of water (approximately 40% of the weight of a root with a dry velamen), corrections must be made when using a fresh weight basis to compare the amounts of acid accumulated by dry and saturated roots. Accordingly, the data for saturated roots have been corrected on the basis of differences in weights of saturated roots and the weights of the same roots dried in air for 5 h.

In plants with fully saturated velamina, acid content rose from 20 to 41 μeq g⁻¹ fresh weight during the dark phase and decreased to 16 during the subsequent light phase. In a second experiment, acid content increased from 12 to 21 μeq g⁻¹ fresh weight during the dark phase.

CO₂ Exchange. The data shown in Figure 2 were obtained in an experiment which gave results representative of those obtained in a similar experiment using plants which had not been watered for several hours and in which the velamen was dry and silvery in appearance. CO₂ uptake commenced within 1 h after the plants entered the dark phase and the rate of uptake increased to a maximum of around 19 μl h⁻¹ g⁻¹ fresh weight after 4 h in darkness, then declined until CO₂ evolution occurred around the subjective dawn (Fig. 2). Illumination at 300 μmol m⁻² s⁻¹ resulted in a decline in the rate of CO₂ evolution to 3 μl h⁻¹ g⁻¹ fresh weight from a rate of 8 μl h⁻¹ g⁻¹ fresh weight which had occurred in the preceding dark period. CO₂ evolution at this lower rate was maintained for 5 h. Illumination at 600 and 900 μmol m⁻² s⁻¹ caused further decreases in the rate of CO₂ evolution. At all light levels investigated, including 900 μmol m⁻² s⁻¹ which approximates the upper levels of irradiation experienced by the plants in the natural environment, net CO₂ evolution was always observed. Transition from light to darkness was followed by a rapid increase in CO₂ evolution.

Effects of Water on CO₂ Exchange. Figure 3 illustrates data representative of four separate experiments carried out on plants in which the velamen was fully engered with water. CO₂ evolution occurred in both dark and light. Illumination at 100 μmol m⁻² s⁻¹ resulted in a transient decrease in the rate of CO₂ evolution from 8 to 4 μl CO₂ h⁻¹ g⁻¹ fresh weight followed by a slow increase to 6 μl CO₂ h⁻¹ g⁻¹ fresh weight at the end of the experiment.

CO₂ exchange was followed in a plant with a dry, silvery velamen until it was clear that dark CO₂ fixation was in progress (Fig. 4). The plant was then sprayed with distilled H₂O until the velamen was soaked. Following this treatment, CO₂ evolution occurred through the remaining 9 h of the dark period. The rate

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**Fig. 1.** Changes in acid content of roots of *C. usneoides* during the diurnal cycle. (O), Means of replicate samples taken at 2-h intervals. (C), Samples taken at the end of acid-accumulating and acid-consuming phases on subsequent days (a 3-fold decrease in scale follows the break in the x axis).

**Fig. 2.** CO₂ exchange in dark and light in *C. usneoides*. Following incubation in darkness at 25°C for 15 h, the plant was illuminated at 300, 600, and 900 μmol m⁻² s⁻¹ PAR. Finally, the plant was returned to darkness. (Negative CO₂ exchange = uptake).

**Fig. 3.** CO₂ exchange in *C. usneoides* with water-saturated velamina. Incubation of the plant at 25°C for 15 h was followed by illumination at 100 μmol m⁻² s⁻¹ PAR. The velamen was saturated with water throughout the experiment.
of release increased from 2 to 11 µl h⁻¹ as the subjective dawn approached. Also plotted on Figure 4 for comparative purposes is the progress curve of CO₂ exchange in the same individual when the velamen was dry throughout the experiment.

Products of Dark Fixation of ¹⁴CO₂. Autoradiography of extracts of small intact plants incubated with ¹⁴CO₂ in darkness for 14 h illustrated that malic acid contained the majority of the radioisotope. In one experiment in which the plant weighed 1.7 g, 96% of the activity was located in malic acid, citric acid contained 3%, and the remainder was accounted for by two unidentified components.

Anatomy of Roots. Figure 5 shows a scanning electron micrograph of the surface and section of cortex of photosynthetic root of C. usneoides. Long scale bar = 100 µm. Arrows indicate apparent aeration pathways through the velamen (a) and exodermis (b) leading to the photosynthetic cortex (c).

Fig. 4. Effect of saturating the velamen on the progress of CO₂ exchange in darkness. CO₂ exchange was followed at 25°C until it was established that a normal CO₂ exchange pattern was developing. At the time indicated, the plant was sprayed with distilled H₂O until the velamen was saturated. (O), CO₂ exchange pattern of the same individual plant when the velamen remained dry throughout the dark period. (Negative CO₂ exchange = uptake).

Fig. 5. Scanning electron micrograph of surface and section of cortex of photosynthetic root of C. usneoides. Long scale bar = 100 µm. Arrows indicate apparent aeration pathways through the velamen (a) and exodermis (b) leading to the photosynthetic cortex (c).

The CO₂ exchange data (Figs. 2 and 4) clearly demonstrate that dry roots of C. usneoides acquire CO₂ from the atmosphere in darkness. The large diurnal fluctuations in acidity measured in the present work substantiate earlier findings (1, 12). Comparison of the kinetics of CO₂ fixation and the kinetics of acid accumulation (Figs. 1 and 2) support the contention that CO₂ fixation leads to acid synthesis and accumulation. Malic acid is the major product of dark ¹⁴CO₂ fixation and, in conjunction with the low ¹³C values reported by Winter et al. (12), this indicates that the nocturnal uptake of CO₂ is via PEP carboxylase.

The acquisition of CO₂ from the atmosphere by gaseous diffusion in land plants has two conflicting aspects, the inward diffusion of CO₂ which there is advantage in maximizing, and the inevitably associated outward diffusion of water vapor which there is advantage in minimizing. C₃, C₄, and most CAM plants utilize the control of gaseous diffusion afforded by stomata to achieve the necessary balance. In CAM plants, apart from the shootless orchids, the stomata allow adequate diffusion of CO₂ into the plant at night and, when closed during the light decarboxylation phase, reduce the outward diffusion of water and CO₂. Since this is not possible in Chilioschista, the question arises as to how this shootless orchid exhibits CAM in the absence of stomata.

Although the roots possess structures specialized to allow gaseous exchange between the atmosphere and the internal gas phase of the plant (i.e., pneumatophores and the special cortical cells described by Benzing and Ott [3] and Benzing et al. [2]), there does not appear to be any possibility for the diurnal regulation of gaseous diffusion as is effected by stomata in the leaves and shoots of CAM plants (Fig. 5). In these photosynthetic roots, gaseous diffusion between internal and external atmosphere takes place across a diffusion barrier over which the plant has no control. The proportion of exchange which occurs through the pneumatophores and the proportion which occurs through the surface of the velamen and underlying tissues remains to be determined. However, regardless of the details of the diffusion pathway, it is certain that the diurnal changes in diffusive resistance which are an essential component of CAM in leaves and stems are not a feature of the photosynthesis of this shootless orchid.

In CAM plants with stomata, leakage to the atmosphere during the light phase is small (10). Despite the absence of stomata in Chilioschista roots, the rate of loss of CO₂ to the atmosphere in the light decarboxylation phase is also low (Fig. 2). The near atmospheric values measured for internal CO₂ concentration in the light in Chilioschista suggest that the slow loss to the atmosphere may be the result of the magnitude of the diffusion gradient of CO₂ between the internal and external atmosphere. It appears that in place of the control of CO₂ loss by control of diffusion resistance found in CAM plants with functional stomata, the loss of CO₂ from Chilioschista in the light phase is minimized by the balance between decarboxylation and photosynthetic CO₂ fixation being regulated such that the level of CO₂ within the roots.

Abbreviation: vpm, volumes per million volumes.
is maintained around atmospheric concentration. Thus, unlike
the situation in other CAM plants (4, 11), the externally directed
diffusion gradient in the light is not great. The biochemical
mechanism which achieves this balance between CO2 release and
consumption remains to be elucidated.

In addition to being high enough to limit water loss to a level
which can be tolerated by the plant, the diffusion resistance of
the roots must obviously also be low enough to allow acquisition
of an adequate supply of CO2. The utilization of PEP carboxylase
in CAM may be important in this context because (unlike
ribulose-1,5-bisphosphate carboxylase/oxygenase) it can operate
effectively at low (virtually zero) CO2 concentrations in air (5)
and therefore has the potential to maximize the inwardly directed
CO2 diffusion gradient into the roots.

Figures 3 and 4 demonstrate that saturation of the velamen
with water has a dramatic deleterious effect on the CO2 exchange
of the plant. The curves show that the amplitude of acid fluctua-
tion is reduced by a factor of about 5 and dark fixation of CO2
is abolished. A superficial explanation would be that saturation
of the velamen increases diffusion resistance—the liquid water
layer acting as a diffusion barrier—thereby reducing inward
diffusion of CO2 and associated acid accumulation. However,
although this may well be part of the answer, the finding that
plants with saturated velamina evolve CO2 in darkness rather
than simply taking up less CO2 indicates that the situation is
complicated. A similar response of CO2 exchange to wetting in the
bromeliad CAM plant Tillandsia usneoides has been reported
by Martin and Siedow (9). Further work is required on this
phenomenon.

The photosynthetic metabolism of shootless orchids represents
an addition to the presently recognized mechanisms by which
plants acquire atmospheric CO2, namely C3, C4, CAM, and the
recently discovered aquatic acid metabolism photosynthesis (7, 8).
Although the metabolism of C. usneoides is clearly derived
from CAM, we consider that the absence of stomatal control of
diffusional resistance represents a significant physiological dis-
tinction and we propose the term astomatal CAM for this variant
of photosynthetic carbon metabolism.

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